(Paper Number)

Evaluation of Cryofreezer Technology through Simulation and Testing (DRAFT)

Molly Anderson and Su Curley
NASA Johnson Space Center

ABSTRACT

A cryofreezer system is being evaluated as a new method of compressing and storing carbon dioxide (CO_2) in an Advanced Life Support (ALS) Environmental Control and Life Support System (ECLSS). A cryocooler is used to provide cold temperatures and heat removal while CO_2 freezes and accumulates around a coldtip. The CO_2 can then be stored as a liquid or high-pressure gas after it has been accumulated. This system was originally conceived as an In-Situ Resource Utilization (ISRU) application for collecting CO_2 from the Mars atmosphere to be converted to methane fuel with a Sabatier reaction. In the ALS application, this system could collect CO_2 from the International Space Station (ISS) Carbon Dioxide Removal Assembly (CDRA) for delivery to the Sabatier reactor. The Sabatier reaction is an important part of proposed Air Revitalization System (ARS) for ALS, and technology sharing is often possible between ISRU and ARS applications in CO_2 processing systems.

A prototype system developed and initially tested by Lockheed Martin Astronautics is now being evaluated in the Air Revitalization Technology Evaluation Facility (ARTEF) at NASA Johnson Space Center (JSC). This paper will discuss testing conducted through December 2004 to examine the performance and capacity of the system under a variety of input conditions. A simulation of the system was developed simultaneously using the Aspen Custom Modeler (ACM) software package. Several approaches using varying levels of detail could be used when modeling the system, and this paper will discuss the assumptions and choices made in this simulation, as well as the validity of the simulation for predicting performance of the prototype unit.

INTRODUCTION

Carbon dioxide removal is recognized as an important function of any spacecraft life support system. As such, it is a high priority function in ALS air revitalization systems, which also include the collection, processing, and recycling of resources. Current ARS baselines for many long-term missions include molecular sieve CO_2 collection technology, oxygen generation through electrolysis of water, and a Sabatier reactor to combine CO_2 and waste H_2 from electrolysis to make water and methane (CH_4). Molecular sieve systems, such as the Carbon Dioxide Removal Assembly (CDRA) used on the (ISS), usually provide CO_2 at a low pressure and a varying flowrate during desorption cycles. A Sabatier reactor generally requires a stream of CO_2 at a constant flow rate and constant higher pressure then that delivered by the molecular sieve systems. Several compression and accumulation technologies have been proposed to fill the gap between the two. Mechanical compressors and solid-state adsorption based compressors are two that are currently being developed and evaluated. A third technology, this cryofreezer concept, involves the freezing of low pressure CO_2 gas at cryogenic temperatures and the melting and pressurization of the collected CO_2 for high-density storage and high-pressure supply.

Cryofreezer Evaulation at JSC

The cryofreezer system has been installed in the ARTEF test bed at JSC for evaluation. Testing will examine the performance of the system under a range of conditions. A simulation of the cryofreezer is being developed in ACM, and a validated simulation will be integrated with simulations of other technologies in the ARTEF to examine the potential integrated applications and support any future integrated testing.

The cryofreezer system – The cryofreezer unit consists of two primary components, a cryocooler and a freezing

chamber.

The cryocooler is capable of cooling the CO_2 down to its very low freezing temperature and removing the heat of phase change. In the test unit, the cryocooler is a pulse tube cryocooler built by the National Institute of Standards and Technology (NIST). This cryocooler is expected to be able to provide at least 35 W of heat removal at –90C to –85C, which are the approximate freezing temperatures of CO_2 at 4psi and 8psi respectively. The cryocooler is expected to provide approximately 23W of cooling power when the coldtip is maintained at –123C, which has been the operating temperature during previous testing. This cryocooler is relatively dated and inefficient compared with state of the art cryocoolers, but it is a sufficient and effective unit for early testing such as this. Any future cryofreezer systems would be designed with more efficient cryocoolers.

The freezing chamber consists of an aluminum vessel that can withstand both the sub-ambient pressures of the input gas stream and the high pressures that can be produced in the cryocooler from the phase change of CO_2 from solid to liquid and gas, a coldfinger, and a copper heat exchanger that distributes the energy removal capacity provided by the cryocooler and collects the frozen CO_2. The freezing chamber is bolted directly to the cryocooler unit. The coldfinger extends down from cryocooler into the freezing chamber and is partially surrounded by a metal heat exchanger. The heat exchanger consists of 16 semicircular disks arranged into a sphere with the coldtip of the coldfinger extending into the center of the sphere as shown in Figure 1.

Figure 1: Cryofreezer aluminum mounting flange and freeze chamber and copper, finned heat exchanger.

This finned, spherical arrangement of the heat exchanger provides several benefits that a single, unaided coldfinger cannot provide. The additional surface area allows faster CO_2 accumulation. The thermal conductivity of the accumulating CO_2 ice ball is increased by reducing the temperature gradient between the coldtip in the center and the ice at the outside edge of the heat exchanger, allowing CO_2 freezing to continue longer. Finally, the heat exchanger fins also allow heat to be conducted back into the CO_2 more rapidly during the melting process. CO_2 melts at the heat exchanger surface first, allowing orange slice like chunks to fall off, maximizing the surface area for heat transfer during melting.

testing – The cryofreezer unit will be tested in the ARTEF test bed at NASA JSC. This initial testing is standalone, though the potential exists to conduct integrated tests between the cryofreezer and other CO_2 collection or processing technologies, such as the ISS CDRA with a Sabatier reactor. The test points were designed to simulate this integrated test configuration.

<u>Test Design</u> - The unit will first be tested at static input conditions to explore the impact that two primary variables will have on its performance: inlet gas pressure and flowrate. The three test points for inlet gas pressure to be examined are 1psi, 4psi, and 7psi. These pressures are in the range that might be expected as an output from four-bed molecular sieve (4BMS) technology such as the ISS CDRA. Pure CO_2 will be provided and a pressure regulator just upstream of the freezing chamber inlet will be used to select the operating pressure.

Flowrate is another possible important parameter in the operation of a cryofreezer unit. Flowrate impacts heat transfer and removes any gases with a lower freezing temperature than CO_2, whether they are trace gases, as in this testing, or larger amounts, such as entrained air in a 4BMS or the other gases that make up the Martian atmosphere for ISRU. A small constant speed DIA-Vac vacuum pump is installed downstream of the cryofreezer unit, and the flowrate will be varied by opening or closing the valve between the freezing chamber and the vacuum pump. A total of seven

positions including full open and full close for the valve will be investigated. A fully closed outlet valve (no bypass flow) would be a likely operation scenario for a cryofreezer used as a compression device downstream of a 4BMS when total recycles and reuse of CO_2 is desired. Bypass flow during a pure CO_2 feed case suggests that some CO_2 is expendable in the ECLSS design. It could be possible to implement a recycle around the cryofreezer to allow flow through the freezing chamber, but no flow exiting the system as a whole.

Additional test points will be performed by slowly ramping the chamber pressure up from 1psi to 7psi and then back down to 1psi during the expected freezing period. This mimics the actual output pressure swing conditions of the CDRA system.

The freezing period usually ends because the cryocooler is unable to remove more heat from the freezing chamber than it is leaking in. As mentioned before, this cryocooler is an older unit with relatively poor efficiency. It can be cooled during the test, but eventually it becomes too hot to be effective. At this point, the inlet and outlet valves are closed, and the cryocooler unit is powered down, discontinuing any cooling. Heat from the ambient air and from the cryocooler is then transferred into the chamber. The metal cold finger and heat exchanger are routes for energy to enter the ice ball of CO_2 during the melting cycle. The CO_2 is allowed to vaporize, and reach a pressure where liquid CO_2 is present. The presence of liquid CO_2 aids heat transfer, and the ice melts and vaporizes at an even greater rate. This process causes the pressure in the chamber to increase rapidly. When the chamber pressure reaches 300 psi, the outlet valve is opened and CO_2 is vented until the freezing chamber is at atmospheric pressure and no CO_2 is exiting the unit.

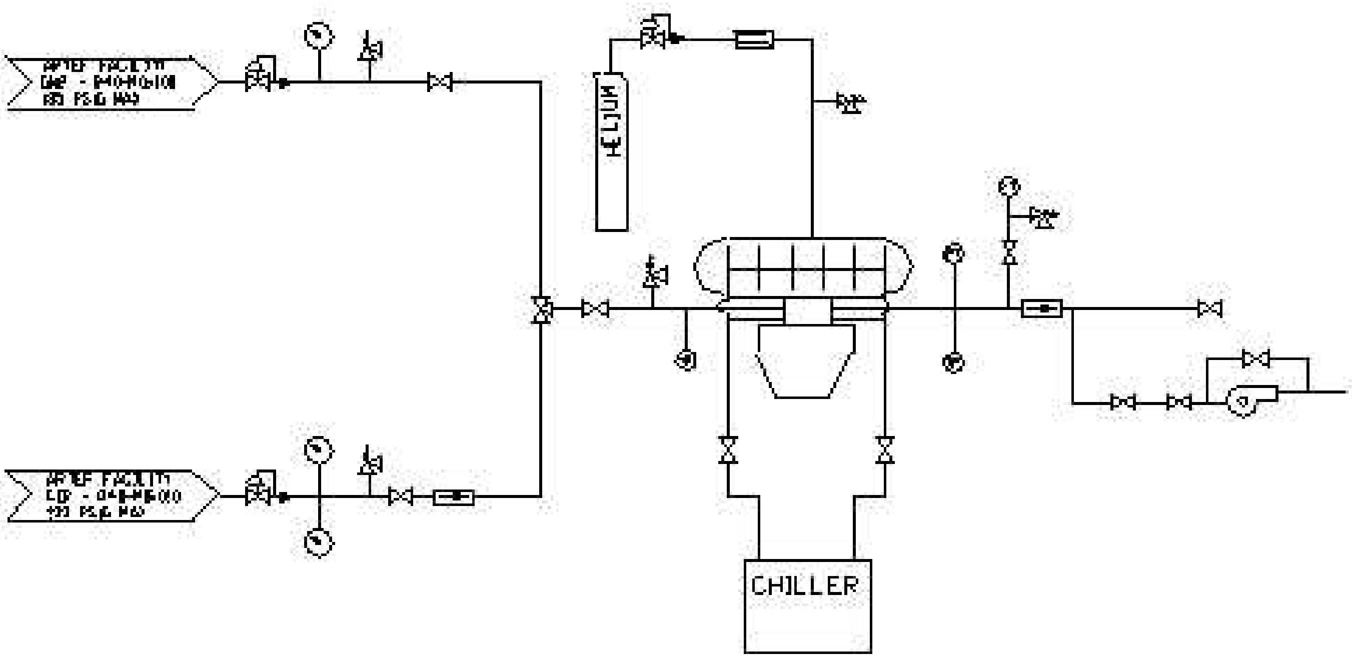

Figure 2: This figure shows the schematic of the test apparatus of the cryocooler and cryofreezer vessel. The cryocooler vessel is represented by the oval with cross-marks that represent cooling water lines wrapped around the body of the unit. The freezing chamber extends below the cryocooler unit. The helium feed provides the pressurized working fluid for the pulse tube cryocooler. Pressure gauges, flow meters, and temperature sensors are present on the inlet and outlet streams. A small vacuum pump is downstream of the exit to pull low-pressure gases through the system for bypass flow.

Test Results – The testing has not yet been conducted, so the results cannot be listed.

Simulation and analysis – Analysis can be an important tool during the examination and testing of a new system. A model that is validated and corresponds well to test data can be an indicator that experimenters understand the underlying principles and actions in the system.

Integration experiments can be conducted with simulation and modeling without the hassles and cost of test build-up to explore what configurations and operating modes may be useful.

Simulating the Cryofreezer – A simulation of the cryofreezer was developed using the ACM equation solver software. An initial model was developed based on the basic mass and energy balances, as well as best estimates of heat transfer coefficients. Models of other air revitalization technology that have been or will be tested in ARTEF have been implemented in ACM, including the CDRA and a Sabatier Engineering Development Unit (EDU). A validated cryofreezer model can be integrated with these systems. Other models can be included either upstream of downstream of the cryofreezer to explore possible results and interactions during integrated testing.

Several of the instruments used for data collection might not be completely necessary for a proof of concept test but are very useful for making sure that the energy balance correctly allocates the various sources of heat energy in the model. One primary question involves how much of the energy removed by the cryocooler comes from the phase change of CO_2 and how much is lost to any gas that may be passing through the chamber. This is accomplished by measuring the inlet and outlet temperature and flowrate of the CO_2 stream. The temperature of the gas phase inside the chamber is measured and contributes to how much energy removal is required to freeze each gram of CO_2 collected, since the gas must first be cooled to the freezing temperature before the phase change can occur. The gas phase temperatures are again significant during the melting cycle. It will be important to learn how much heat is channeled back into the chamber from the overheated cryocooler as compared to the heat that is transferred through the chamber walls from the environment. If most of the heat comes from the cryocooler, as is suspected, a more efficient cooler in a future design may not provide enough heat for a quick melt cycle.

The cryofreezer unit was modeled for simulation in two parts. A simple model of the cryocooler was constructed to predict the amount of heat removal provided by the NIST cryocooler at various coldtip temperatures. One benefit of using ACM as a simulation tool is the modularity of the simulations conducted. This cryocooler model can easily be replaced with one that represents a new cryocooler to construct a new integrated cryofreezer simulation. It may also eventually be replaced with a more detailed model, if the designers of a new cryocooler reveal more details than are currently available on the unit used in testing discussed in this paper.

The freezing chamber model is used to calculate the rate at which CO_2 freezes and accumulates and then melts. During a freezing cycle, CO_2 ice is modeled as a simple sphere with lumped parameters. The simulation compares the heat removal ability of the cryocooler to the estimated amount of heat leaked into the system through the coldfinger and the heat transfer from gas in the chamber, which cools as it flows past the heat exchanger and ice ball. If the heat removal is greater than the sum of the routes of heat entering, any difference is used to freeze CO_2.

Simulation Results – This simulation will address how the model was correlated and validated with test results, what can be learned from the modeling and simulation that might not be immediately visible from test results, and any future modeling plans, including improvements and integrated test simulations.

In future simulations where there is a high amount of nonfreezing gas present, it may be necessary to calculate diffusion of CO_2 through these gases. However, these cases will almost certainly not be conducted with zero exit flow during the freeze phase, and the mixing may be sufficient that the diffusion calculation is not necessary. Future tests will show whether this change is needed.

Conclusion

Once the testing is completed, we will likely have several conclusions to discuss. They may include whether the performance of the unit suggests it will be suitable for integration with a CDRA. Design aspects that should be improved for a redesign could be included, and it will be useful to mention that it is probably still to early to compare this unit with other CO_2 compression technologies. Any possible other uses or system impacts for the technology may also be considered. The conclusion should also address any changes or improvements that need to be made to the model for further work and whether the assumptions were sufficient to represent the system. Future testing plans will likely be mentioned as well.

Acknowledgments

Thanks to Larry Clark, LM Astronautics, for providing the cryofreezer and continuing support during the buildup, analysis, and testing of the system.

References

1. Clark, D., K. Payne, J. Trevathan. “Carbon Dioxide Collection and Purification System for Mars.” AIAA 2001-4660. Space 2001 Conference and Exposition. Albuquerque, NM. 28-30 August 2001.
2. Cryofreezer Test Plan Document still needs an official JSC document number

CONTACT

Molly S. Anderson
Lockheed Martin Space Operations
2400 NASA Road 1, C70, Houston TX 77058
molly.s.anderson@lmco.com

Su Curley
NASA Johnson Space Center
2101 NASA Road 1, EC3, Houston, TX 77058
su.curley-1@nasa.gov

Definitions, Acronyms, Abbreviations

ACM: Aspen Custom Modeler

ALS: Advanced Life Support

ARTEF: Air Revitalization and Technology Evaluation Facility

CDRA: Carbon Dioxide Removal Assembly

ECLSS: Environmental Control and Life Support System

EDU: Engineering Development Unit

ISS: International Space Station

JSC: Johnson Space Center

4BMS: Four-bed molecular sieve